Investigation into the bond between CFRP and steel tubes

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ABSTRACT: CFRP material has been widely used to strengthen concrete structures. There is an increasing trend of using CFRP in strengthening steel structures. The bond between steel and CFRP is a key issue. Relatively less work has been done on the bond between CFRP and a curved surface which is often found in tubular structures. This paper reports a study on the bond between CFRP and steel tubes. A series of tensile tests were conducted with different bond lengths and number of layers. The types of adhesive and specimen preparation methods varied in the testing program. High modulus CFRP was used. Tests were carried out to measure the modulus and tensile strength of CFRP. Strain gages were mounted on different layers of CFRP. The stress distributions across the layers of the CFRP were established. Models were developed to estimate the maximum load for a given CFRP arrangement.

1. INTRODUCTION

Carbon fiber reinforced polymer (CFRP) have been successfully used to strengthen structural elements made of concrete [Teng et al. 2000]. A limited amount of research has been conducted on the application of CFRP to steel structures [Moriarty & Barnes 1998, Tani et al. 2000, Moy 2001, Miller et al. 2001, Tavakkolizadeh & Saadatmanesh 2003a,b, Jiao & Zhao 2004]. Carbon fiber composites, that weigh approximately one-tenth of what steel does, can be adhesively bonded, and can have stiffnesses comparable to that of steel. Their high strength-to-weight ratio has played a significant role in creating interest in strengthening, repair and rehabilitation of metallic structures [Hollaway & Cadei 2002, Tumialan et al. 2002, Cederquist 1999]. In addition, their non-reactive and corrosion resistant properties mean that the materials can be used in areas where deterioration from environmental conditions pose a problem for traditional materials [Andres & Torres-Acosta 2002, Karbhari & Shulley 1995, Tavakkolizadeh & Saadatmanesh 2001, Bassetti et al. 2000]. Research has shown the potential of using CFRP overlays for prolonging the fatigue life of steel sections [Tavakkolizadeh and Saadatmanesh 2003b, Bassetti et al. 2000, Sean et al. 2003]. Some research has also been conducted for steel bridge [Miller et al. 2001, Liu et al. 2001], steel beams [Nikouka et al. 2002, Moy 2000], and steel concrete composite structures [Tavakkolizadeh. & Saadatmanesh 2003b,c, Rajan et al. 2001]. It is important to note that life cycle costs associated with composite structures become attractive to owners because of the limited need for continual maintenance and future rehabilitation. Recently CFRP was used to strengthen butt welded very high strength (VHS) tubes [Jiao & Zhao 2004]. The strength reduction in the heat-affected-zone was successfully recovered using the CFRP technique. However there is a lack of understanding of the bond characteristics between CFRP and steel tubes. In the present study the bond behaviour of CFRP and steel circular tubes is investigated.

Tensile tests were conducted to measure the modulus and stress-strain relationship of the CFRP used. Several tests were carried out to examine the bond between CFRP and steel tubes. Load transfer and slip between the top layer and steel tubes are discussed. The strain distributions across CFRP layers and along the CFRP length were established. The load carrying capacity was predicted with reasonable accuracy.

2. MATERIALS

2.1 CFRP

In the present research, MBrace fiber CF530 was chosen. Mbrace CF530 is so called high modulus (640 Gpa) CFRP as compared with CF130 (240Gpa). The specified properties of Mbrace CF530 are listed in Table 1.

Table 1. Properties of MBrace CF 530 specified by the manufacturer

Fibre reinforcement	Carbon – High Modulus
Fibre density	2.1g/cm^3
Fibre Modulus	640 GPa
Fibre weight (CF)	400 g/ m^2
Thickness	0.19mm
Tensile strength	2650 MPa
Tensile Elongation, Ultimate	0.4%
Design tensile force @ 0.2% strain /m width	200 kN
Roll Length	50m
Sheet width	300mm

2.2 Adhesives

High strength Araldite 420 adhesive was selected. Experiments showed that this was a suitable adhesive for steel structures [Jiao & Zhao 2004].

2.3 Steel tubes

The steel tubes were provided by One Steel Market Mills Australia. They are similar to those used in a previous research project on strengthening butt-welded tubes [Jiao & Zhao 2004].

3. MEASUREMENT OF MATERIAL PROPERTIES OF CFRP

Tensile tests were conducted to verify the modulus and tensile strength specified by the manufacturer. Three tensile tests were conducted separately for the FRP with and without epoxy.
The length and width of the specimen were 400mm and 50mm, respectively. At the two ends of CFRP sample, steel plates were attached to grip the CFRP to the machine. Two strain gages were fixed on both sides of the CFRP and positioned at the centre of the sample. Figure 1 shows the test setup for the tensile test.

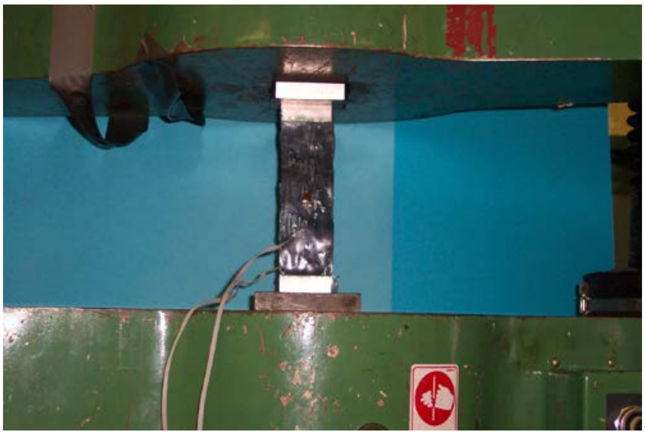

Figure 1. Typical test specimen of tensile test.

The stress vs strain curves are shown in Figure 2. Measured properties are summarized in Table 2. The large values of COV reflect possible variations in the test setup. Tests are being carried out to investigate this further.

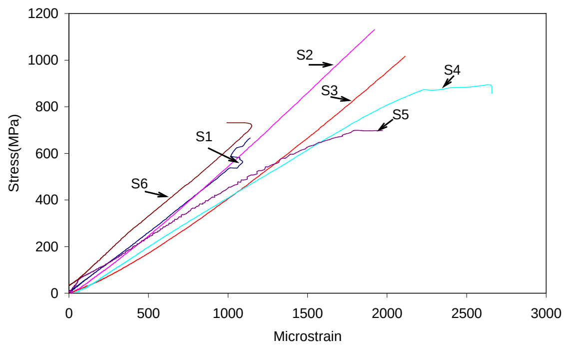

Figure 2. Stress vs Strain curves

Table 2.Measured properties of CFRP

Sample ID	With Epoxy	Length (mm)	Width (mm)	Modulus E (Mpa)	Maximum Strain ε_{max} (Microstrain)	Maximum Stress σ_{max} (Mpa)
S_1	Yes	400	50	530397	1139	666
S_2	Yes	400	50	581250	1921	1130
S_3	Yes	400	50	475905	2113	1016
S_4	No	400	50	409264	2660	858
S_5	No	400	50	449537	1970	698
S_6	No	400	50	603962	1148	720
Average				508386	1825	848
COV				0.1505	0.3232	0.2237

4. SPECIMENS FOR BOND TESTING

The first step in sample preparation was the preparation of steel surface to which the CFRP sheets were bonded. Surface grinders or sandblasters were used to remove all rust, paint, and primer from the tube surface along the bond length and the cross sectional surfaces where the two tubes were joined together. Another purpose of using grinder or sandblaster was to make the surface rough to ensure better bonding. The cross sectional surfaces of the tubes were then cleaned using Acetone. Adhesive was then used at these surfaces of the tubes to join two tubes. The sample was cured for one day and postcured for about 24 hours at a controlled temperature of about 70^0C.

The tube surfaces were cleaned using acetone to apply adhesives. Thin coat of adhesive was applied uniformly to the CFRP sheet and on steel tube surfaces up to the bond length mentioned in Table 3. The selection of bond length is based on the findings by Jiao and Zhao 2004. The findings also suggested that any anchorage length beyond 65 mm would produce similar results. Steel tubes were then wrapped by one layer CFRP sheet. The excess epoxy and air (if any) were removed using a ribbed roller, applying it in the direction of the fiber. Sufficient time was allowed to settle the bonding before adding another layer to avoid the possible void between two layers. In this manner, five layers of CFRP were wrapped on the tubes. The whole specimen was then cured for at least one week and postcured for about 24 hours at about 70^0C.

5. BOND TESTS

5.1 Instrumentation

Several 'student type' strain gages were attached to each test specimen. Figures 3(a), (b) and (c) show the location of each gage. Strain gages were placed at the short side of the bonded CFRP to capture the longitudinal strain development along the CFRP and the tube. One strain gage (G1) was placed inside the tube at a position 20 mm from the joint. The 2nd strain gage (G2) was placed on the 1st layer of CFRP laminate, at 20 mm from the joint. The 3rd strain gage (G3) was placed on the 3rd layer, 20 mm away from the joint. The 4th Strain gage (G4) was applied at the top layer at the joint of the two tubes. The 5th strain gage (G5) was applied at the top layer, 20 mm away from the joint. All other strain gages at the top layer were applied along the tube at 12 mm distance from each other. The number of gages used in each sample, thus, depends on the bond length of that specimen.

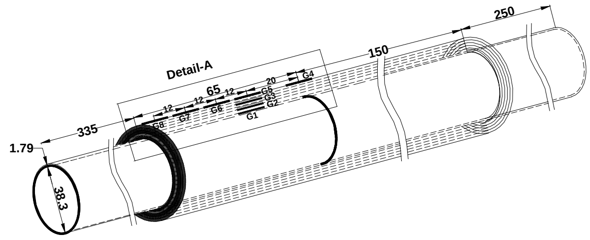

Figure 3(a). Location of strain gages.

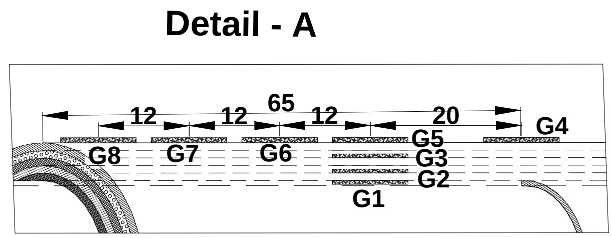

Figure 3(b). Detail A of Figure 3(a).

Figure 3(c). Typical specimen with strain gages.

LVDT was instrumented to record the relative slip between CFRP and steel. String pot was placed to measure the gross vertical movement of the tube. Crack propagation in CFRP was recorded by a high speed video recorder.

5.2 Test setup and test procedure

Each tube was loaded in a Baldwin Universal Testing machine as shown in Figure 4, at a loading rate of 2.0mm /min and 500 KN load range. The test procedure consisted of applying increasing tensile loads to the specimen and recording the accompanying strain data. The test was continued until failure of the specimen.

Figure 4. Test set up for steel tube wrapped with CFRP under tensile loading.

6. TEST RESULTS

The failure modes and ultimate loads obtained in the tests are presented in Table 3 where t is the tube thickness. The failed specimens are shown in Figure 5. Specimen M_2 shows different failure mode from other specimens. Fiber break failure together with adhesive failure were observed in this specimen. This specimen failed at much lower load than other specimen. It is believed that when part of the adhesive failed, probably because of improper wrapping, then the CFRP couldn't hold the rest of the load and failed by fiber break at a lower load. This phenomena clearly indicates that preparation of specimen is very much important in CFRP bonding as it can influence the ultimate bond strength.

Table 3. Test results

Specimen Label	D mm	t mm	l_1 mm	l_2 mm	P_u KN	Failure Mode
M_1	38.24	1.84	85	150	84.9	Fiber break
M_2	38.22	1.83	75	150	42.2	Fiber break & Adhesive failure
M_3	38.30	1.79	65	150	74.1	Fiber break
M_4	38.10	1.60	62	112	77.5	Fiber break
M_5	38.27	1.74	50	100	67.3	Fiber break

Figure 5. Typical failure mode of test specimen.

7. LOAD TRANSFER

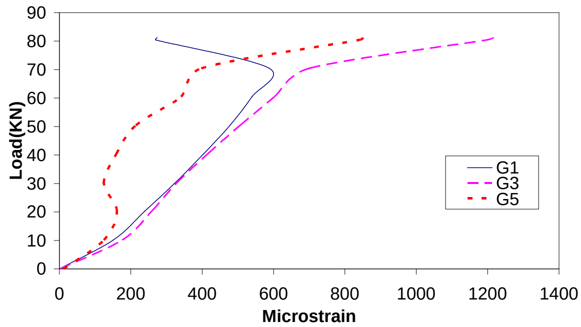

Figure 6. Microstrain vs Load curve for a typical specimen.

The rehabilitation/repair or strengthening scheme, to a great extent, depends upon load transfer. From the strain distribution profiles the evolution of the load transfer process can be determined. Load is transferring from steel to the CFRP first layer then the CFRP second layer up to the top layer. Thus, there is load sharing between CFRP and steel. The dominant failure mode observed here is 'fiber break failure'. For a typical test, the strain readings at different load level recorded by different strain gages through the layers of CFRP are shown in Figure 6. In the case of G3 and G5 the whole fibre did not break or tear at once. When a portion of the fibre was broken, the remaining portion of fiber carried the additional load before the final failure. Figure 6 shows that when load is transferred to the remaining portion of the CFRP, strain on these fibres increased significantly.

G1 and G3 show almost identical strain distribution before failure starts. In the case of G1, the gage installed on the steel tube, the strain reading after failure is different from the strain reading G3 and G5, gages installed on CFRP. In G1, the strain decreases rapidly during failure, because, unlike CFRP, there is no additional fibre to carry the load. The strain pattern before failure in G5 is different from that of G1 and G3. The strain pattern of G5 before failure shown in figure is mainly because of slip between the top layer and the steel tube, as can be seen in Figure 7. That's why the top layer reading is lower than the inside layer reading. The strain distributions are as used later in the paper. Whether the same results could have been established by using flat steel plates with CFRP bonding is under investigation at present.

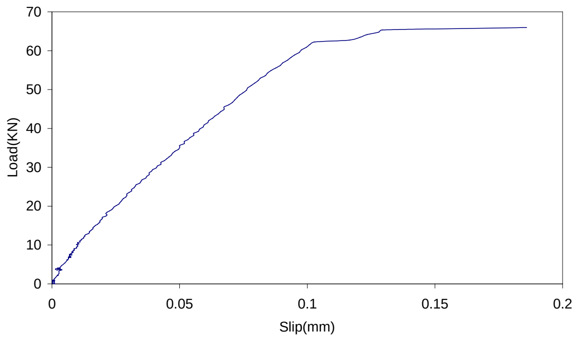

Figure 7. Relationship of Slip between CFRP and steel tube [specimen M_5].

8. STRAIN DISTRIBUTION

8.1 *Distribution across layers*

One of the main objectives of this study is to determine the distribution of strain across the CFRP layers and also along the CFRP. To perform this task, strain was measured at 1st (bottom), 2nd, 3rd and 5th (top) layer of CFRP (G1, G2, G3 and G5) at same location away from the joint. Strain was also measured at different locations away from the joint on top layer (G4, G5, G6, G7 and G8). The strain gage locations are shown in Figures 3(a) (b) & (C).

Figure 8 shows the variation of strain at different CFRP layers under different load ratio. The load ratio is defined as ratio of applied load to the maximum load achieved in the text. Figure 8 is based on the average strain readings of all specimens. There is a general trend of decreasing in strain from the bottom layer to the top layer. The trend is very much the same for all load ratios. In order to derive an expression of strain in terms of layer numbers, non-dimensional strains ($\varepsilon/\varepsilon_1$ where ε_1 is the strain in layer one) are plotted against layer numbers in Figure 9. A regression line can be determined using Excel as shown in Figure 9 where y refers to the vertical axis and x represents the horizontal axis. This regression expression is simplified in this paper to the following equation:

$$\varepsilon_i = \frac{\varepsilon_1}{\sqrt{i}} \qquad (1)$$

where i is the layer number (i = 1, 2, 3, 4, or 5), ε_i is the strain in the ith layer.

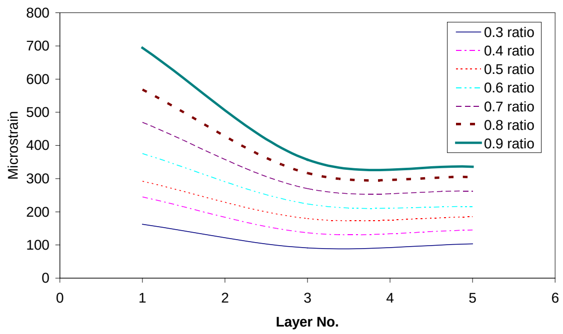

Figure 8. Distribution of strain through FRP layers at different load level.

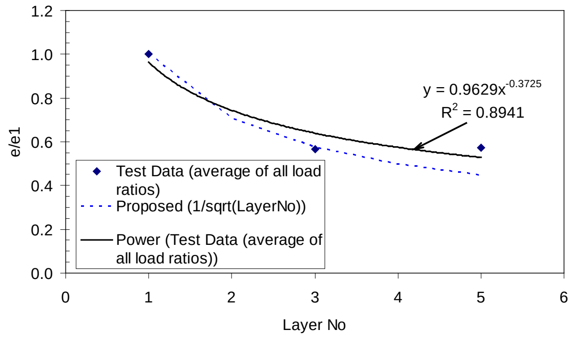

Figure 9. Non-dimensional strain versus CFRP layer Numbers.

8.2. Distribution along CFRP

To study the distribution of strain along the length of CFRP, strain at different distances away from the joint in the top layer is shown in Figure 10. Similar to Figure 8 the strain distribution is plotted at different load levels. It is clear from the figure that strain generally decreases with the distance away from the joint. The decreasing trend do not seem to be consistent because the reading in gage G7 located about 44 mm away from the joint is higher than that in G6 located about 32 mm away from the joint. More tests are needed in order to obtain a reliable expression of strain distribution along CFRP length.

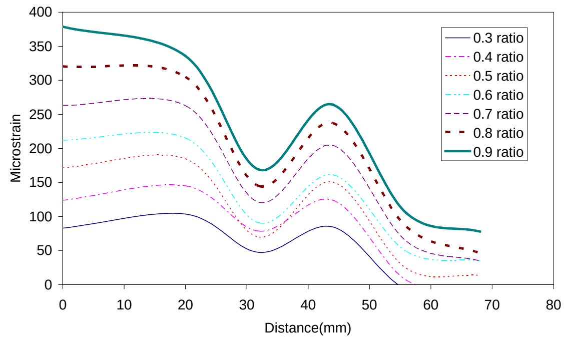

Figure 10. Distribution of strain at top layer at different load level.

9. LOAD CARRYING CAPACITY

9.1 Stress distribution at the ultimate state

The strain at the ultimate state can be expressed as:

$$\varepsilon_{i,u} = \frac{\varepsilon_{1,u}}{\sqrt{i}} \qquad (2)$$

where $\varepsilon_{i,u}$ is the ultimate strain in the ith layer, $\varepsilon_{1,u}$ is the ultimate strain in the first (bottom) layer.

The corresponding stress in the ith layer can be written as:

$$\sigma_{i,u} = E \cdot \varepsilon_{i,u} = E \cdot \frac{\varepsilon_{1,u}}{\sqrt{i}} \qquad (3)$$

where E is the modulus of CFRP.

9.2 Load carrying capacity

The load carried by each CFRP layer (P_i) can be calculated as the product of the area of that layer (A_i) and the ultimate stress in that layer ($\sigma_{i,u}$). The total predicted load carrying capacity (P_p) can be written as:

$$P_p = \sum A_i \cdot \sigma_{i,u} = \sum A_i \cdot E \cdot \frac{\varepsilon_{1,u}}{\sqrt{i}} \qquad (4)$$

The value of $\varepsilon_{1,u}$ is taken as the maximum strain (2113 microstrain) obtained in the tensile test of CFRP with epoxy given in Table 2. The corresponding modulus of 457,905 MPa is taken as E in the calculation of P_p in this paper.

The predicted load carrying capacity is listed in Table 4 where specimen M_2 is not included due to a premature failure. The predicted values are compared in Table 4 with experimental ultimate load (P_u). A mean ratio (P_p/P_u) of 1.003 is achieved with a coefficient of variation (COV) of 0.098.

Table 4. Comparison of load carrying capacity.

Specimen Label	P_u (KN)	P_p (KN)	P_p/P_u
M_1	84.9	75.7	0.891
M_3	74.1	75.8	1.023
M_4	77.5	75.4	0.973
M_5	67.3	75.7	1.125
mean			1.003
COV			0.098

10. CONCLUSIONS

The following conclusions and observations are made based on the limited test results.

1. The average measured modulus of CFRP was found to be 508 GPa which is slightly lower than the manufacturer specified modulus 640 GPa. The measured tensile strength of CFRP was found to be significantly less than 2650 MPa specified by the manufacturer.
2. The dominant failure mode observed in the CFRP bond test was fiber break failure. The method of specimen preparation was found to be important.
3. The slip between the top layer and steel tubes might be the reason for non-uniform strain distribution among the layers.
4. The strain distribution across the layers was established as shown in Eq. (1).
5. The strain was found to generally decrease along the CFRP length away from the joint.
6. The estimated load carrying capacity was found to be in close agreement with that obtained experimentally.

ACKNOWLEDGEMENT

The authors acknowledge the contribution of Graeme Rundle and Kevin Nievaart for the setup of the test equipment. MBT, Vantico & OneSteel Market Mills, Australia Pte Ltd provided Fiber, Epoxy and steel tubes, respectively.

REFERENCES

Andres, A. and Torres-Acosta, 2002. Galvanic Corrosion of Steel in Contact with Carbon-Polymer Composites. I: Experiments in Mortar. Journal of Composites for Construction, ASCE, May . 6(2): 112-122.

Bassetti, A., Nussbaumer, A., Manfred, A.2000. Crack Repair and Fatigue Life Extension of Riveted Bridge Members Using Composite Materials. Bridge Engineering Conference, ESE-IABSE-FIB, 26-30 March. Vol 1, 227-238.

Cederquist, S.C.1999. Repairing America's deteriorating bridges. Materials Performance, 38(5): 20-25.

Hollaway, L. and Cadei J.2002. Progress in the technique of upgrading metallic structures with advanced polymer composites. Progress in Structural Engineering and Materials, 131-148.

Jiao, H. and Zhao, X.L. 2004. CFRP Strengthened Butt-Welded Very High Strength (VHS) Circular Steel Tubes, *Thin-Walled Structures,* 42:963-978

Karbhari, V.M. and Shulley, S.B.1995. Use of Composites for Rehabilitation of Steel Structures- Determination of Bond Durability. Journal of Materials in Civil Engineering,ASCE, Nov. 7(4): 239-245.

Liu, X., Silva, P.F. and Nanni, A.2001. Rehabilitation of Steel Bridge Members with FRP Composite Materials. Proc., CCC2001, Composites in Construction, Porto, Portugal, Oct. 10-12, 613-617.

Miller, T.C., Chajes, M.J., Mertz, D.R., and Hastings, J.N.2001. Strengthening of a Steel Bridge Girder using CFRP Plates. Journal of Bridge Engineering, ASCE, 6(6): 514-522.

Moriarty, J. and Barnes, F.1998. The Use of Carbon Fiber Composites in the London Underground Limited Civil Infrastructure Rehabilitation Program. SAMPE Journal, 34(2): 23-28.

Moy, S.S.J.2000. Early Age Curing Under Cyclic Loading-A Further Investigation into Stiffness Development in Carbon Fibre Reinforced Steel Beams. Department of Civil and Environmental Engineering, University of Southampton, UK, Sep.

Moy, S.S.J.2001. FRP Composites: Life Extension and Strengthening of Metallic Structures. ICE Design and Practice Guides. London: Thomas Telford. 64.

Nikouka, F., Lee, M. and Moy, S.2002. Strengthening of Mettalic Structures using Carbon Fibre Composites. IABSE Symposium, Melbourne.

Rajan, S., Larry., L. and Gray., M.2001. Strengthening Steel Bridge Sections using CFRP Laminates. Composites Part B: Engineering, Vol 32, 309-322.

Sean, C.J., Scott, A. C. and Civjan, P.E.2003. Application of Fiber Reinforced Polymer Overlays to Extend Steel Fatigue Life. Journal of Composites for Construction, ASCE, Nov. 7(4): 331-338.

Tani, K., Matsumura, M., Kitada, T., and Hayashi, H. 2000. Experimental Study on Seismic Retrofitting Method of Steel Bridge Piers by using Carbon Fiber Sheets. in 6th Korea-Japan Joint Seminar on Steel Bridges. Tokyo, Japan. 437-445.

Tavakkolizadeh, M and Saadatmanesh, H. 2001. Galvanic Corrosion of Carbon and Steel in Aggressive Environments. Journal of Composites for Construction,ASCE, August, 5(3): 200-210.

Tavakkolizadeh, M. and Saadatmanesh, H. 2003a. Strengthening of Steel-Concrete Composite Girders using Carbon Fiber Reinforced Polymers Sheets. Journal of Structural Engineering, ASCE, 129(1): 30-40.

Tavakkolizadeh, M. and Saadatmanesh, H.2003b. Fatigue Strength of Steel Girders Strengthened with Carbon Fiber Reinforced Polymer Patch. Journal of Structural Engineering, ASCE, 129(2): 186-196.

Tavakkolizadeh, M. and Saadatmanesh, H.2003c. Repair of Damaged Steel-Concrete Composite Girders using Carbon Fiber-Reinforced Polymer Sheets. Journal of Composites for Construction, ASCE, Nov . 7(4): 311-322.

Teng, J.G.2000. Chen, J.F., Smith, S.T., and Lam, L., FRP Strengthened RC Structures. New York: Wiley.

Tumialan, G., A. Nanni, T.Ibell, and H. Fukuyama, 2002. FRP composites for strengthening civil infrastructure around the world. SAMPE journal, 38(5): 9-15.